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Regional bioelectrical impedance analysis: applications in health and medicine

Abstract Although skeletal muscle mass represents the largest organ in the human body and plays a critical role in energy metabolism, its routine assessment has been limited by the availability of practical methods. This review critically evaluates traditional and new applications of the four-electrode bioelectrical impedance method in determining regional skeletal muscle mass or volume and assessing muscle function in health and disease. It also describes opportunities for research in the use of regional bioelectrical impedance.

Key words Regional body composition • Muscle resistivity • Muscle function

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Introduction

The capability of determining skeletal muscle mass or volume precisely and accurately is beneficial to diverse biomedical disciplines ranging from monitoring of growth and development in healthy individuals to assessing efficacy of interventions in patients with chronic disease. Although methods are available to measure muscle mass, they are impractical for routine use because of inaccessibility and prohibitive cost [1]. Two cost-effective approaches that overcome these limitations have been proposed.

Anthropometry, which uses measurements of circumferences and skinfold thicknesses of one or more limbs, has been used to estimate regional and whole-body muscle mass. Problems with accuracy have generally limited the use of anthropometry in longitudinal studies, particularly when small changes are anticipated [1].

An alternative approach is the four-electrode or tetrapolar bioelectrical impedance analysis (BIA), which measures impedance and assumes specific resistivities of constituent tissues to estimate limb muscle volume [2]. The tetrapolar BIA method has only received limited use to date.

This review critically examines various approaches and applications of the tetrapolar BIA method in assessing regional muscle mass and volume. It highlights limitations of the method and recommends opportunities for future research including the use of BIA in evaluation of impairments of muscle function in neurological disease.

Determinations of regional muscle volume and mass

Attempts to estimate the muscular component of a limb have focused on the upper arm and the leg. Brown et al. [2] compared the accuracy of anthropometry [3] and a single-frequency [1 mA, alternating current (AC), 50 kHz] impedance system in measuring upper arm muscle and fat areas in healthy adults in relation to computed tomography (CT). They used source (spot) electrodes placed on both hands and detector (band) electrodes placed 69 cm apart on the upper arm. To calculate muscle area, they employed a parallel resistance model in which bone cross-sectional area was calculated [3] and the resistivity of skeletal muscle (1.18 ohm·m) was assumed [4]. Among 8 women and 12 men, aged 23–63 years, upper arm resistance ranged from 18.2 to 30.2 ohm and was significantly correlated with CT determinations of muscle area (r=0.961). Areas of fat and muscle determined with CT and impedance were significantly correlated (r=0.945 and 0.981, respectively). Similarly, anthropometric determinations of fat and muscle areas were significantly correlated with CT measurements (r=0.876 and 0.943, respectively). Mean differences between CT and impedance predictions of fat (0.73±2.7 cm^2; mean±SD) and muscle (–0.22±1.87 cm^2) were not statistically different from 0. In contrast, the mean difference between the CT and anthropometric estimates of fat (2.61±3.41 cm^2) and muscle (–2.62±3.14 cm^2) were significantly different from 0. Thus, anthropometry significantly underestimated fat and overestimated muscle. These findings provided the first evidence of the validity and accuracy of the BIA method in determining limb muscle and emphasized the advantage of BIA compared to anthropometry.

Fuller at al. [5] used magnetic resonance imaging (MRI) to evaluate and compare anthropometry and BIA in predicting muscle volume in the lower limbs of healthy adults (8 women and 8 men) aged 41–62 years. Impedance measurements at 50 kHz were made with a multifrequency impedance device. Source electrodes (adhesive strips) were positioned at the base of the fingers and toes of the left hand and foot, with detector electrodes placed on the anterior aspect of the left thigh and the posterior aspect of the left calf. The areas measured in the thigh and calf were a 20-cm and a 10-cm section, respectively. A parallel equivalent model was used with assumed resistivities of skeletal muscle (1.49 ohm·m) to calculate muscle volume. Impedance values were 22.8±5.3 (mean±SD) and 25.2±7.0 ohm for the 20-cm thigh and 10-cm calf sections, respectively; MRI muscle volume determinations were 2.3±0.6 and 0.6±0.1 cm^3, respectively. There was no significant difference in correlation coefficients obtained between MRI and anthropometric estimates of muscle mass compared with those between MRI and BIA index (length^2/impedance; L^2/Z) for the thigh (r=0.59 and 0.68) and calf (r=0.83 and 0.90). Muscle volume was substantially overestimated by 40% in the thigh and 18% in the calf with anthropometry as compared to generally better predictions with BIA for muscle, with an overestimation of 10% in the thigh and an underestimation of less than 5% in the calf. However, both methods demonstrated considerable individual variability with 95% limits of agreement ranging from 20% to 70% with BIA and anthropometry, respectively. In general, there was similar reproducibility for anthropometry and BIA measurements in the thigh (3.5 vs. 3.8%, respectively) but BIA was better than anthropometry in the calf (4.5 vs. 8.5%, respectively). These findings demonstrate the high precision and improved accuracy of estimating regional muscle volume with the single-frequency BIA method compared to anthropometry.

Regional BIA has also been used to monitor muscle mass during weight loss. Twelve obese women aged 21–38 years underwent measurements of whole-body and regional-body composition with dual X-ray absorptiometry and impedance measurements of the right thigh before and periodically during a 4-month controlled weight-loss program of energy restriction and increased physical activity [6]. Source electrodes (adhesive strips) were placed on the right hand and foot and detector electrodes were affixed to the anterior thigh at distances of 15–20 cm depending on the length of the femur. An 800-µA current, AC, at 50 kHz was introduced and impedance was measured. Intraindividual variability in regional impedance was less than 1% during weight stability. Before weight loss, impedance measured at the thigh was significantly correlated with thigh muscle mass (r=0.88). An average weight loss of 22% of initial body weight resulted in a 30% decrease in thigh volume with a 3% reduction in thigh muscle mass. The overall range in observed impedance for this sample was 8–12 ohm during weight loss. Women with the largest loss of muscle mass in the thigh (5%) experienced the greatest increase in impedance measured at the thigh (4%). Impedance normalized for distance between the detector electrodes (L^2/Z) was significantly correlated (r=0.92) with thigh muscle mass. These observations show that regional BIA is a sensitive indicator of longitudinal changes in thigh muscle mass.

BIA and muscle function in health and disease

Another experimental approach for measuring limb muscle volume is the use of contact electrodes. Miyatani et al. [7] developed a BIA acquisition system that uses an 800-µA current, AC, at 50 kHz, and measures upper and lower body impedance. The equipment uses separate contact electrode systems. For measurement of upper body impedance, the BIA system uses two sets of hand-grip electrodes that contain source and detector electrodes separated by a distance of 15 cm and embedded in plastic rods. To measure upper arm impedance, detector (spot) electrodes are placed at the shoulder and elbow. For lower body measurements, two foot-plate electrodes with current-introducing electrodes are placed at the toe and detector electrodes are positioned at the heel of each foot-plate at 16-cm intervals. Alternatively, detector (spot) electrodes may be positioned on the thigh above the knee and at the hip. Upper body measurements are made with the subject seated at a table, and lower body determinations are obtained with the individual standing with equal body mass distributed on each foot. Reproducibility of impedance measurements was found to be very good with an intraclass correlation coefficient of 0.96–0.989 for ten adults measured on two consecutive days with a repeatability coefficient of 3–10 ohm (5–7%).

The impedance index (L^2/Z) of each limb in the upper (forearm and upper arm) and lower limb (thigh and lower leg) was significantly correlated (r=0.90–0.98) with MRI determinations of regional muscle mass in 22 young men [7]. Differences between impedance-predicted muscle volumes were similar (p>0.05) to muscle volumes determined with MRI.

Muscle function, assessed as peak muscle torque, was related similarly to muscle volume and the impedance index [7]. Isometric torque developed in elbow flexion and extension and knee flexion and extension was significantly correlated with MRI determinations of muscle volume of the related muscle group (r=0.80–0.96). Similarly, L^2/Z of the upper arm and thigh was also significantly correlated (r=0.77–0.94) to the torque value. The findings that impedance, corrected for the length of the limb measured, predicts muscle volume and function (e.g., torque) just as well as MRI does, provide additional evidence of the validity of single-frequency impedance as a noninvasive method of assessing regional muscle mass.

Localized BIA recently has been applied to provide new diagnostic information on neuromuscular diseases. This approach is a slight modification of the traditional BIA method; it retains use of an 800-μA current, AC, at 50 kHz, but employs multiple detector electrodes along the limb to determine spatial relationships of localized bioelectrical parameters [8]. It relies on the fact that current applied to muscle travels in both longitudinal and transverse pathways, thus, impedance is much lower for electrical currents flowing parallel to muscle fibers than for currents flowing transverse or across them [9]. This model permits determinations of effective resistivity, which is the resistance measured per unit length of the thigh, and the phase or the arc tangent of the ratio of reactance to resistance and an index of the integrity of the cell membrane, which are hypothesized to reflect integrated neuromuscular function and status [9].

This adapted BIA method uses source (strip) electrodes that are placed on the posterior aspect of the calf on the leg to be measured and the anterior aspect of the contralateral thigh. Multiple detector (strip) electrodes are attached at constant spacing to the anterior surface of the thigh. Interestingly, the thigh is heated to promote penetration of electrolyte conductive gel and thus to reduce contact impedance artifacts between the electrode and skin [9].

Rutkove et al. [10] characterized a normal phase (10.1±1.8 degrees; mean±SD) and resistivity (122±17 ohm·cm) for the thighs of 45 healthy adults. In contrast, 25 patients with neuromuscular diseases had substantially reduced phase (<7 degrees) and markedly increased resistivities ranging from 140 to 300 ohm·cm. Case study data showed a progressive decrease in phase from 10.5 to 4 degrees with minimal change in resistivity during a 500-days period in a patient with amyotrophic lateral sclerosis. Another patient with polymyositis demonstrated a phase value less than the range of normal values and decreased muscle strength. In response to corticosteroid therapy, the patient showed increased strength and normalized phase values. Interestingly, the change in phase preceded any other diagnostic or prognostic measure. These initial findings indicate the potential value of localized BIA as a practical method of noninvasively assessing neuromuscular integrity and function.

Research opportunities

This concise review highlights some successful applications of regional BIA in assessing limb muscle composition and function. It also provides some insight into areas that require additional research and evaluation.

Standardization of electrodes and their placements remains a major concern. There is inconsistency in the type and size of electrode that minimizes contact impedance interferences and optimizes current density and distribution. Although a variety of spot electrodes are used, there is a lack of information on which type yields the best reproducibility and accuracy in prediction models. Another question is the value of spot as compared to band electrodes. Theoretically, band or circumferential electrodes should provide a homogenous environment for optimal introduction of current and measurement of voltage drop. Conversely, reproducibility may be compromised with repositioning errors.

The true in vivo value for skeletal muscle resistivity is a fundamental yet unanswered question. Although some reference values are available, they are very different and quite variable. Estimates of resistivity are complicated by the reliance on two-electrode measurement techniques and the use of ex vivo determinations. Basic studies are needed to discern the effects of subcutaneous adipose tissue as well as inter- and intramuscular fat on measurements of in vivo resistivity.

Additional research is needed to examine the accuracy of regional BIA in longitudinal studies of change in limb muscle. Studies during weight loss and therapeutic interventions are required to determine the validity and sensitivity of the method. Such studies are particularly needed to confirm and extend the initial findings in patients with neuromuscular and other chronic diseases.

Another area of inquiry is the comparison of single- and multiple-frequency impedance devices for assessment of regional muscle distribution and function. Is there additional information that may be obtained with frequencies higher than 50 kHz?

The appeal of BIA lies in its safety, practicality, and non-invasive nature. Recent applications for regional or limb composition assessment are encouraging. Increased use of regional BIA as a simple, cost-effective assessment tool for neuromuscular function is promising.

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